



Optimized Rotorcraft Propulsion System

Abstract

The propulsion system of rotorcraft vehicles is the most critical system to the vehicle in terms of safety and performance. The propulsion system must provide both vertical lift and forward flight propulsion during the entire mission. Whereas propulsion is a critical element for all flight vehicles, it is particularly critical for rotorcraft due to their limited safe, un-powered landing capability. This unparalleled reliability requirement has led rotorcraft power plants down a certain evolutionary path in which the system looks and performs quite similarly to those of the 1960's. By and large the advancements in rotorcraft propulsion have come in terms of safety and reliability and not in terms of performance. The concept of the optimized propulsion system is a means by which both reliability and performance can be improved for rotorcraft vehicles. The optimized rotorcraft propulsion system which couples an oil-free turboshaft engine to a highly loaded gearbox that provides axial load support for the power turbine can be designed with current laboratory proven technology. Such a system can provide up to 60% weight reduction of the propulsion system of rotorcraft vehicles. Several technical challenges are apparent at the conceptual design level and should be addressed with current research.



System Analysis and Performance Benefits of an Optimized Rotorcraft Propulsion System

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Optimized Rotorcraft Propulsion System

Optimized Engine Concept



- ★ Many rotorcraft, especially military, utilize the same lubricant in the engine and transmission to reduce logistics (oil storage, handling, and delivery, single lube system)
- ★ This leads to a compromise in lubricant performance in one or both systems

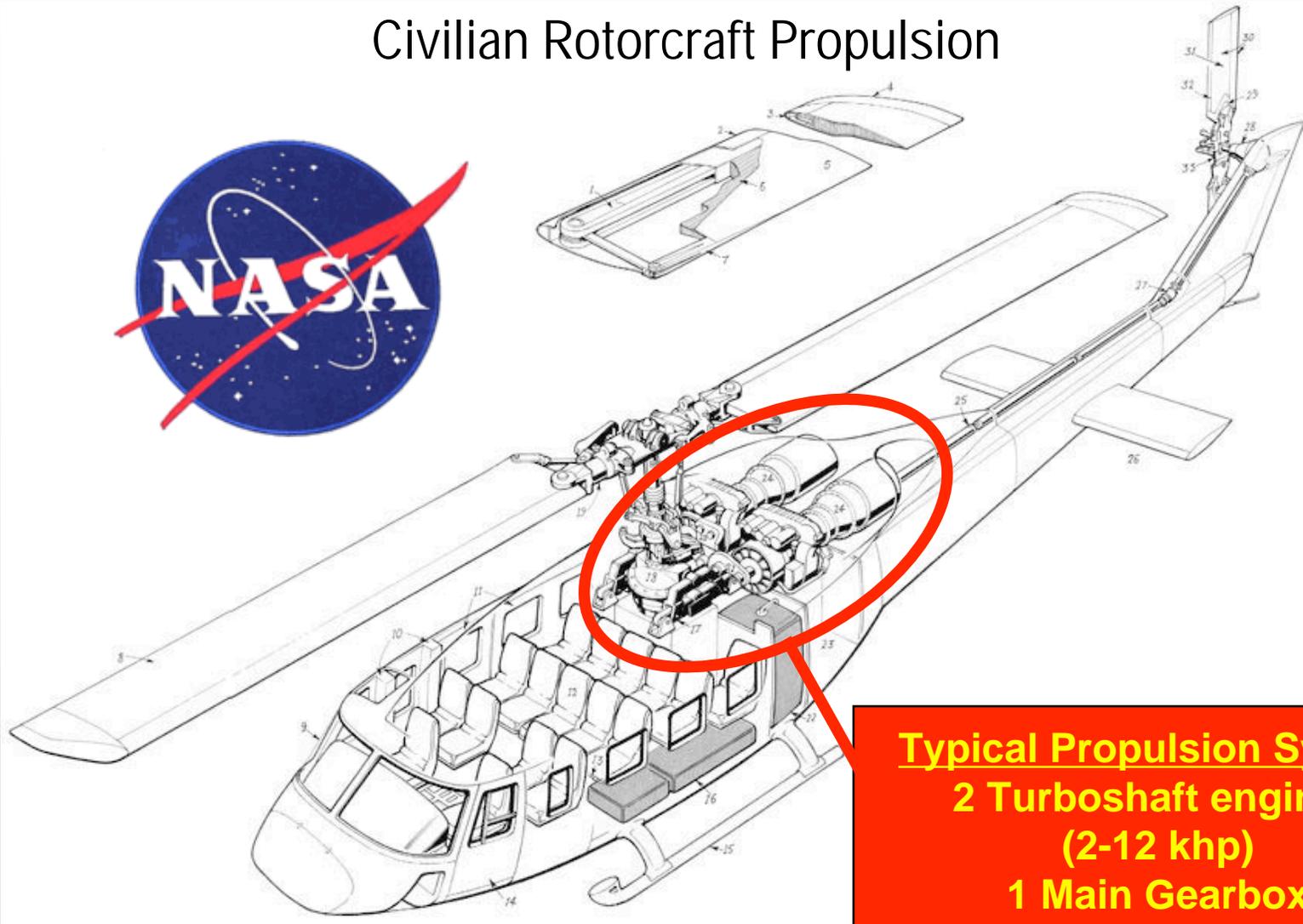
- ★ Due to the high temperature demands of the engine, the transmission often suffers the most, being forced to run with light weight turbine oil as the lubricant.





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Civilian Rotorcraft Propulsion



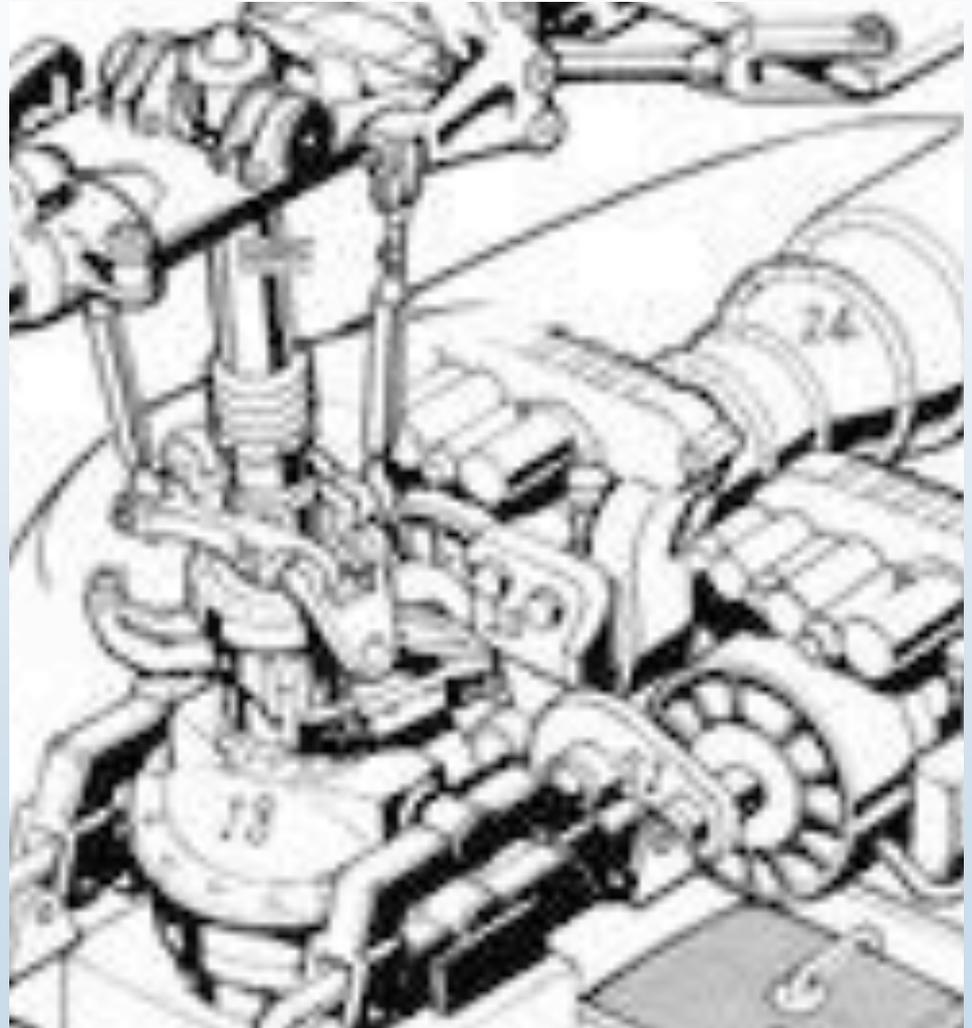
Typical Propulsion System
2 Turboshaft engines
(2-12 khp)
1 Main Gearbox



Optimized Rotorcraft Propulsion System

Rotorcraft Propulsion

- Rotorcraft propulsion systems (engine and transmission) typically use a common lubricant.
 - Typically turbine oil
 - Weight savings and reduced logistical burden
- The result is compromised performance of the transmission lubricant
- US NAVY has pioneered the use of dual lubricants in rotorcraft
 - Corrosion protection additives are incorporated in the transmission lube.
- The current state of the art
 - 25% of RC empty weight is propulsion system (~13% for FW aircraft)
 - 5-7 hp / pound for TS engine
 - 3 hp / pound for gearbox





Optimized Rotorcraft Propulsion System

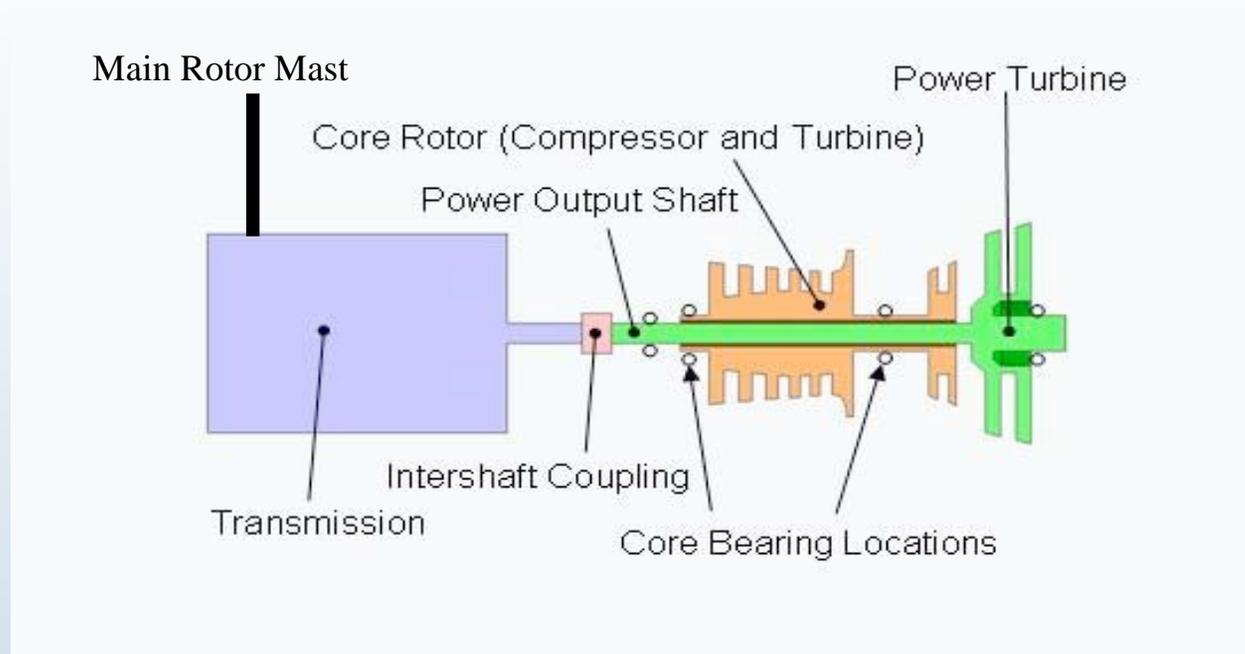
Optimized Engine Concept

- ★ **Research by Townsend and Shimski (NASA TM 106663, 1994) has shown that using a heavier weight gear oil formulated for transmissions can yield an 8+ fold improvement in gear surface fatigue life.**
- ★ **Use of better transmission lubricants can potentially reduce maintenance costs and down time.**
- ★ **The optimized engine concept takes advantage of advances in foil air bearings to couple an Oil-Free engine to a transmission with an optimized lubricant.**



Optimized Rotorcraft Propulsion System

Optimized Rotorcraft Propulsion System

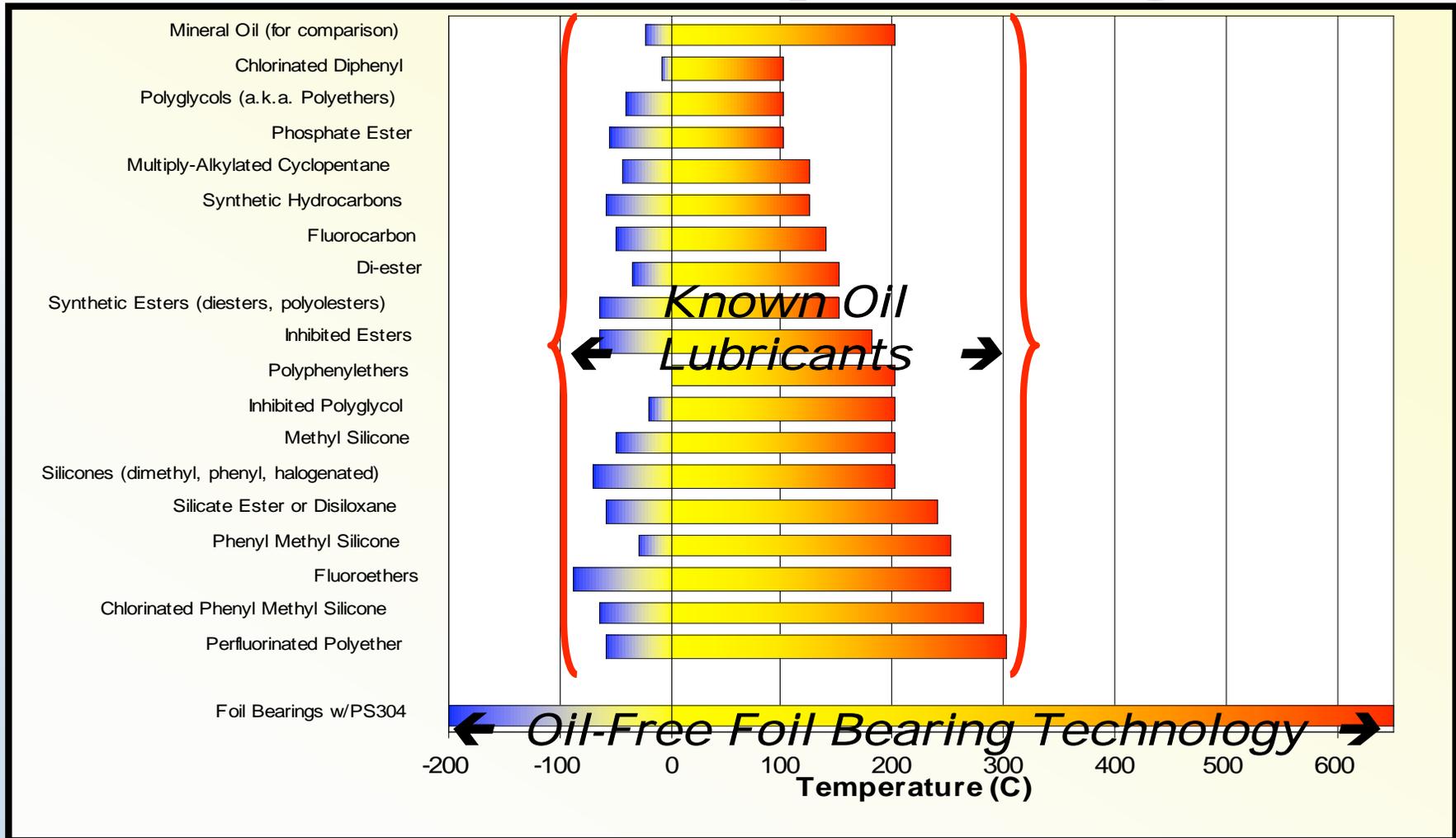


- Foil air bearing supported turboshaft engine with low spool thrust load sharing.
- High power density transmission using high viscosity gear oil
 - “single lubricant” logistics are maintained
 - Enhanced life and reduced weight in transmission
 - Higher power/weight and reduced maintenance in turboshaft



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Lubrication Temperature Ranges

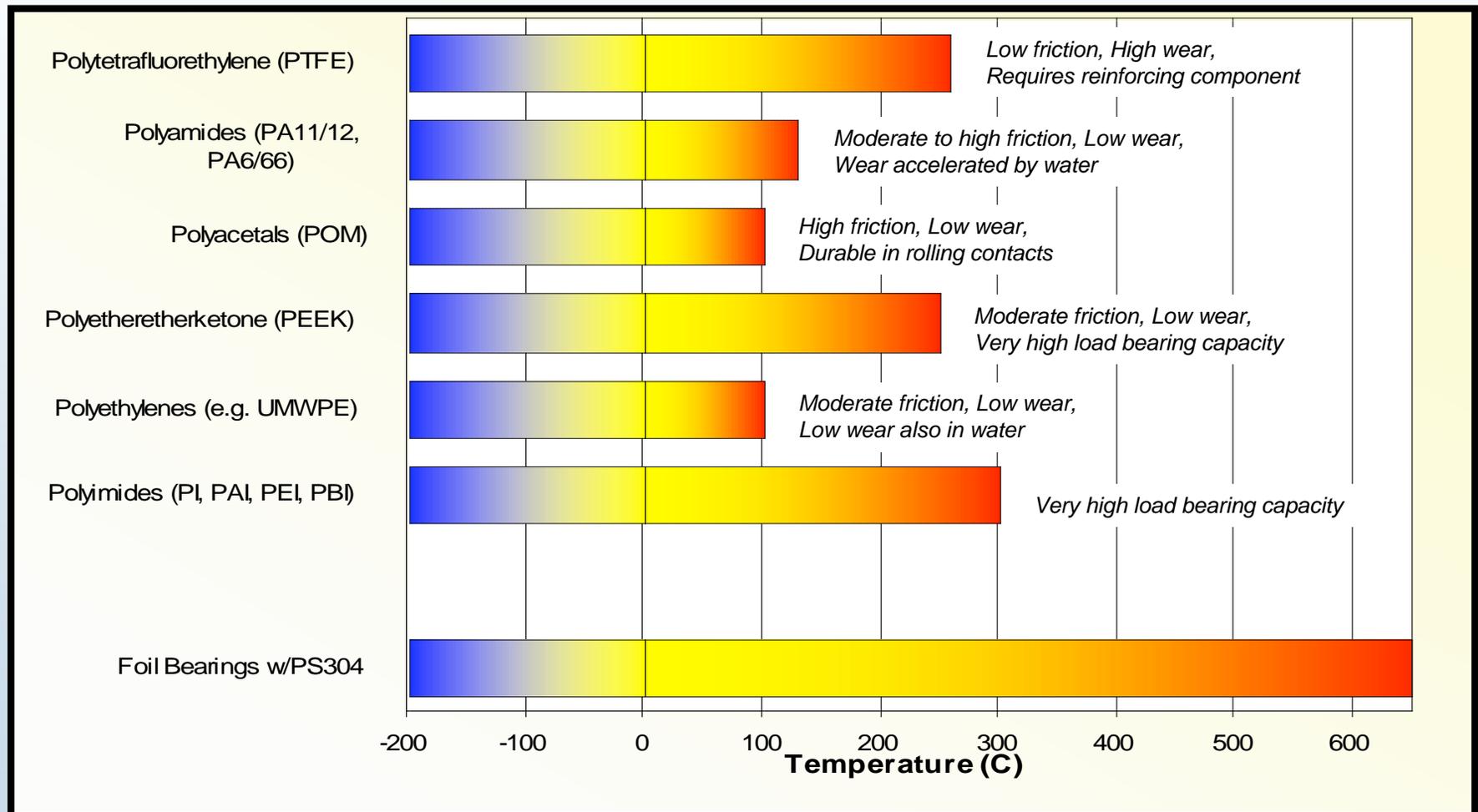


Sources: Neale, "Lubrication – A Tribology Handbook," SAE, 1993, pp. 12-13
Gear Technology, Randall Publishing, Inc., Sep/Oct 2000, p. 18



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Temperature Ranges: Polymers vs. Foil Bearings-PS300

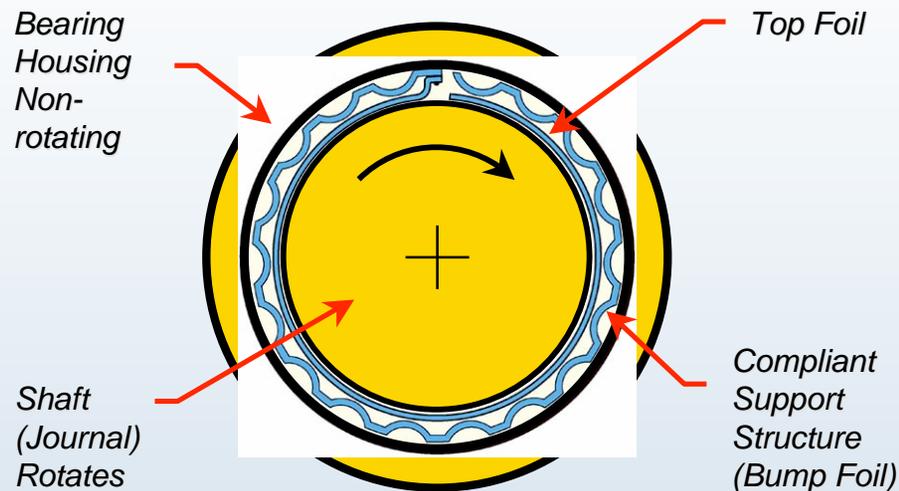


Source: Stachowiak and Batchelor, 1993



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Enabling Technology: Advanced Foil Bearings



Recent design improvements have doubled load capacity, enabling application to a broad range of Oil-Free turbomachinery

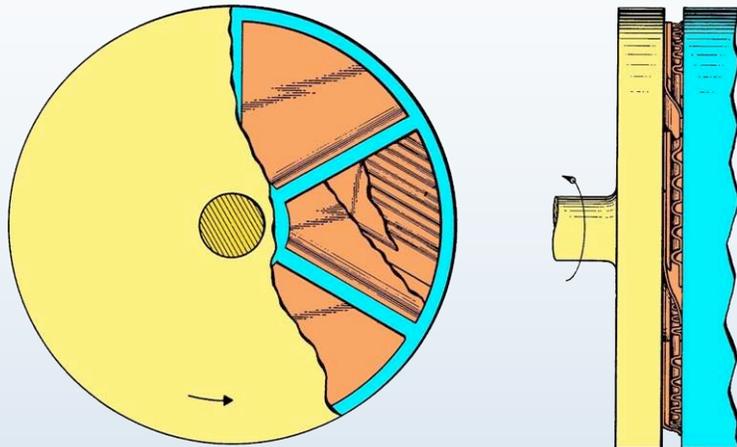
Foil Bearing Benefits:

- ✓ Self-acting hydrodynamic “float on air”
- ✓ No DN speed limit
- ✓ No lube/tanks/coolers/plumbing/filters
- ✓ Operate to 1200°F
- ✓ Compliant “spring” foil support
- ✓ No maintenance
- ➔ No external pressurization
- ➔ Higher power density
- ➔ Lower weight
- ➔ Higher efficiency
- ➔ Accommodate misalignment & distortion
- ➔ Reduce operating costs

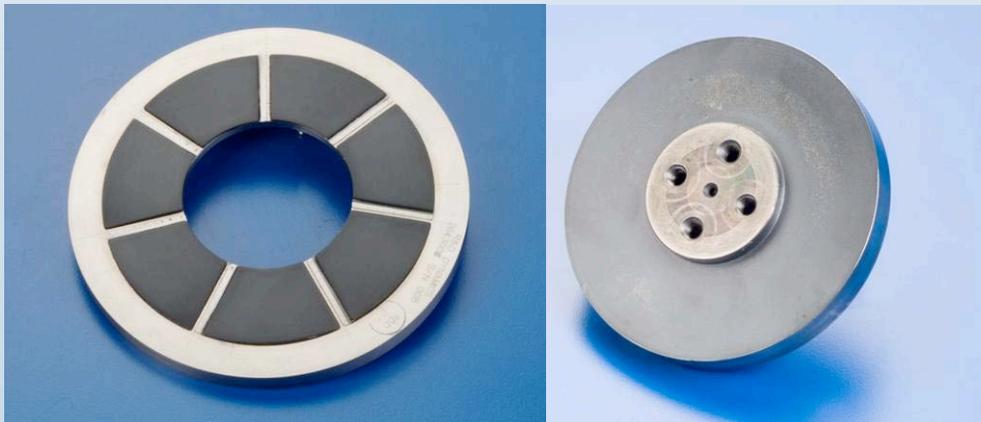


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Foil Thrust Bearings



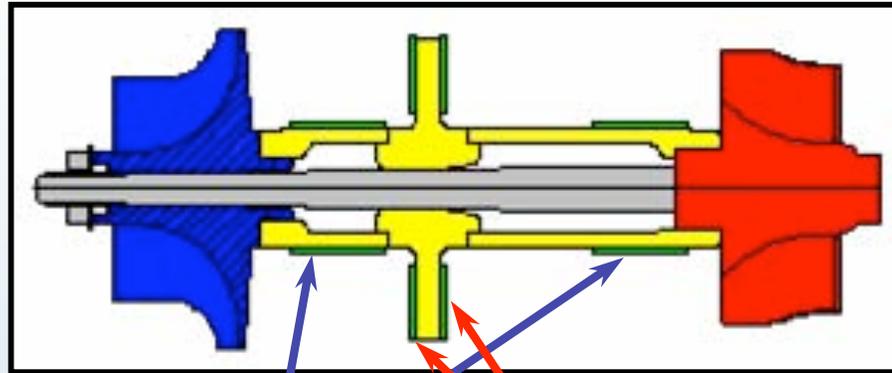
- Hydrodynamically similar to Journal Bearings
- Accommodate Turbomachinery Thrust / Axial Loads
- Multi-pad designs
- Compared to the journal, thrust bearings have received little research attention to date



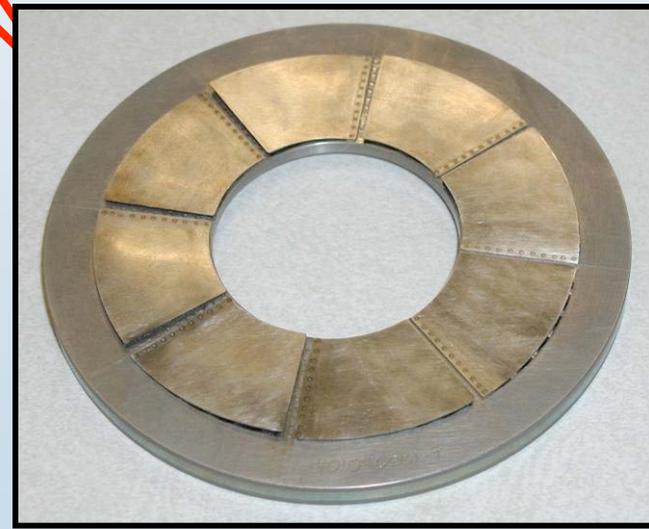


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Journal & Thrust Foil Bearings



Journal Foil Bearing



Thrust Foil Bearing



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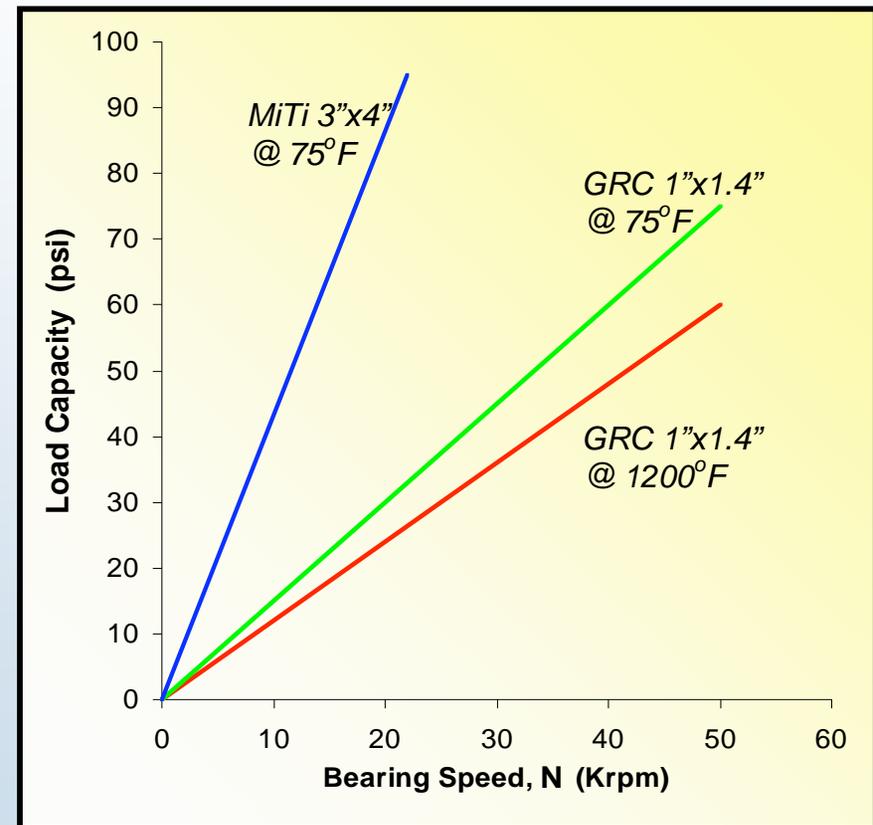
Load Capacity – Foil Air Bearings

Rule of Thumb

... a journal foil bearing will support about one pound per square inch of projected area per inch of bearing diameter per thousand rpm

$$\text{Load} = D_j (L \times D) \times D \times N$$

Data Source	L (in)	D (in)	N (Krpm)	D_j (lb*min/in ³)	Load (lb)
GRC	1.0	1.4	50	1.0	98
MiTl	3.0	4.0	22	1.1	1,140



**Extrapolating load capacity for a 30-50,000 lb thrust class engine
2 bearings, 6"x6" at 18,000 rpm with $D_j = 1.0$ support 7,800 lbs**



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Load Capacity -- Thrust Bearings

Rule of Thumb

... a thrust foil bearing will support about one tenth of a pound per square inch of projected area per inch of brg mean diameter per thousand rpm

$$\text{Load} = D_t (\pi W \times D_m) \times D_m \times N *$$

Oil-Free turbocharger requirement

135 lbs at 95,000 rpm

$$D_t = 0.07$$

Thrust foil bearing testing

$$D_t = 0.12$$



* R.O.T. for thrust bearings requires further validation



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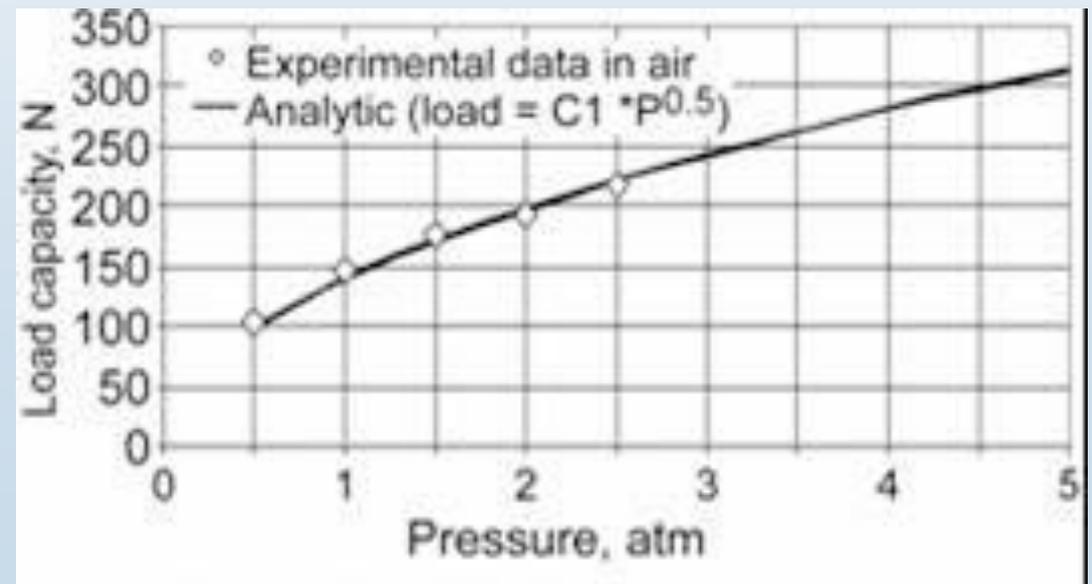
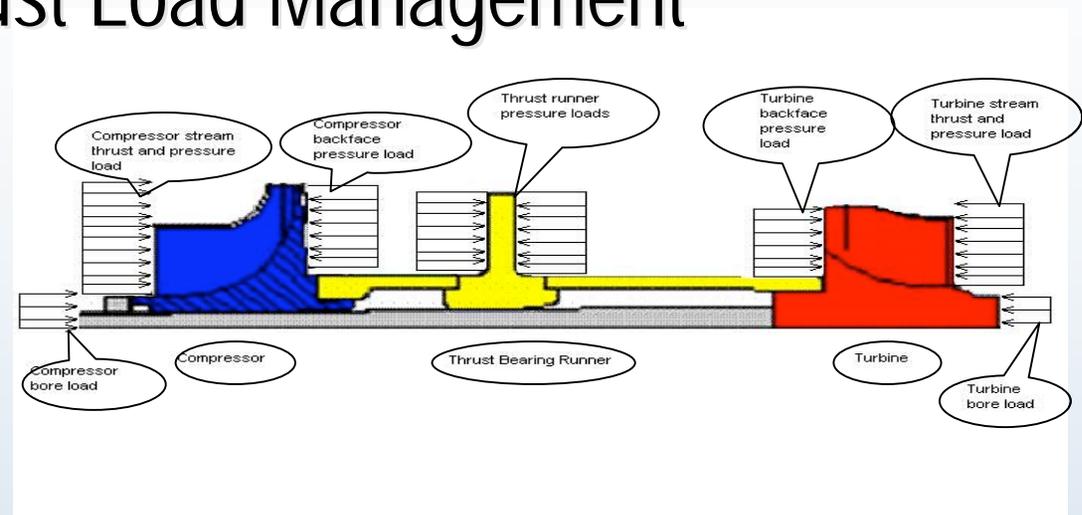
System Thrust Load Management

- Rotating spool thrust loads are imposed by stream thrust, pressure, and attitude angles

- Inter-stage seal radius design selection can control total thrust load that the thrust bearing must counteract.

- Foil bearing load capacity increases with bearing cavity ambient pressure.

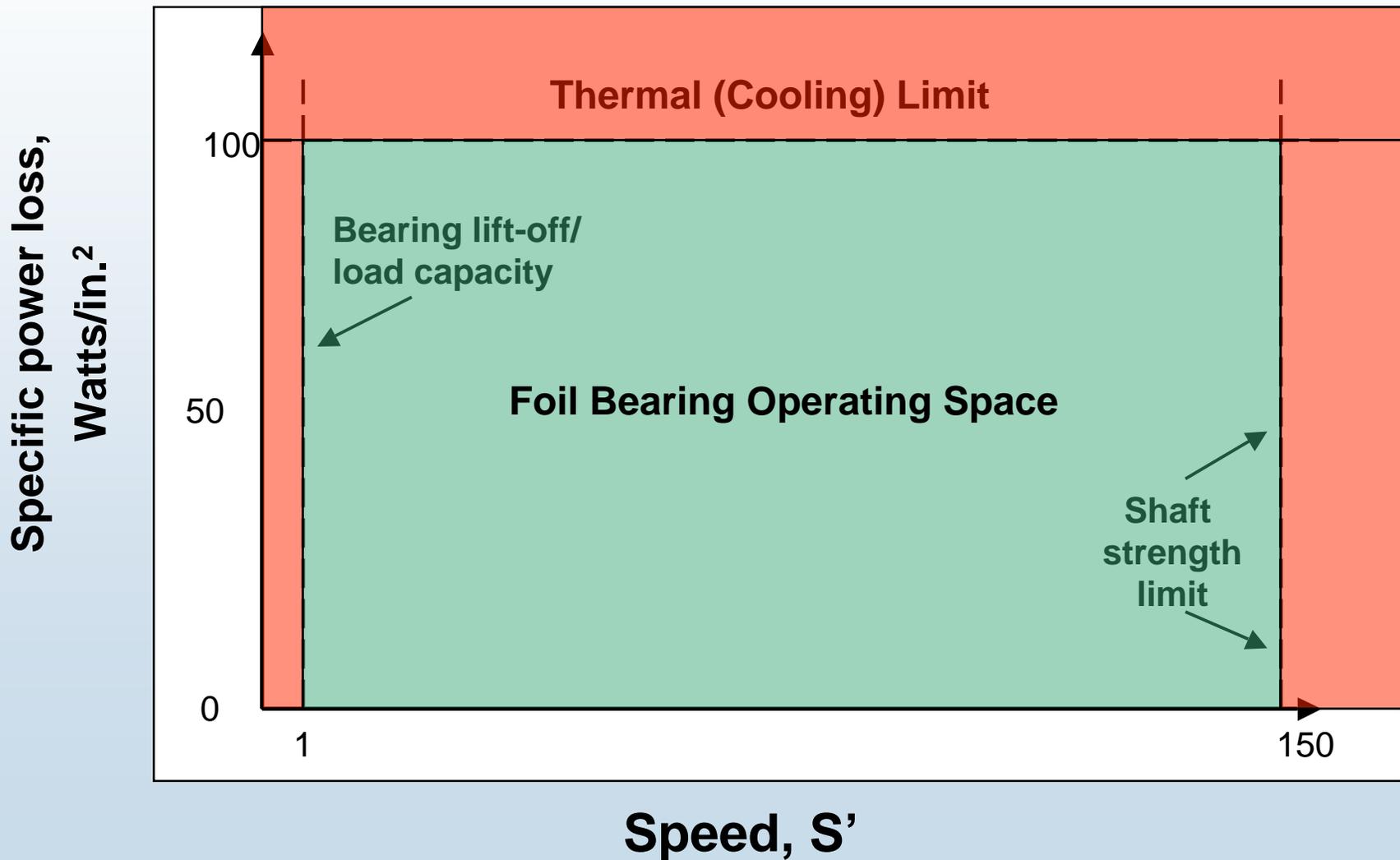
- The high pressure spool can be fully supported by foil bearings in the radial and axial directions.





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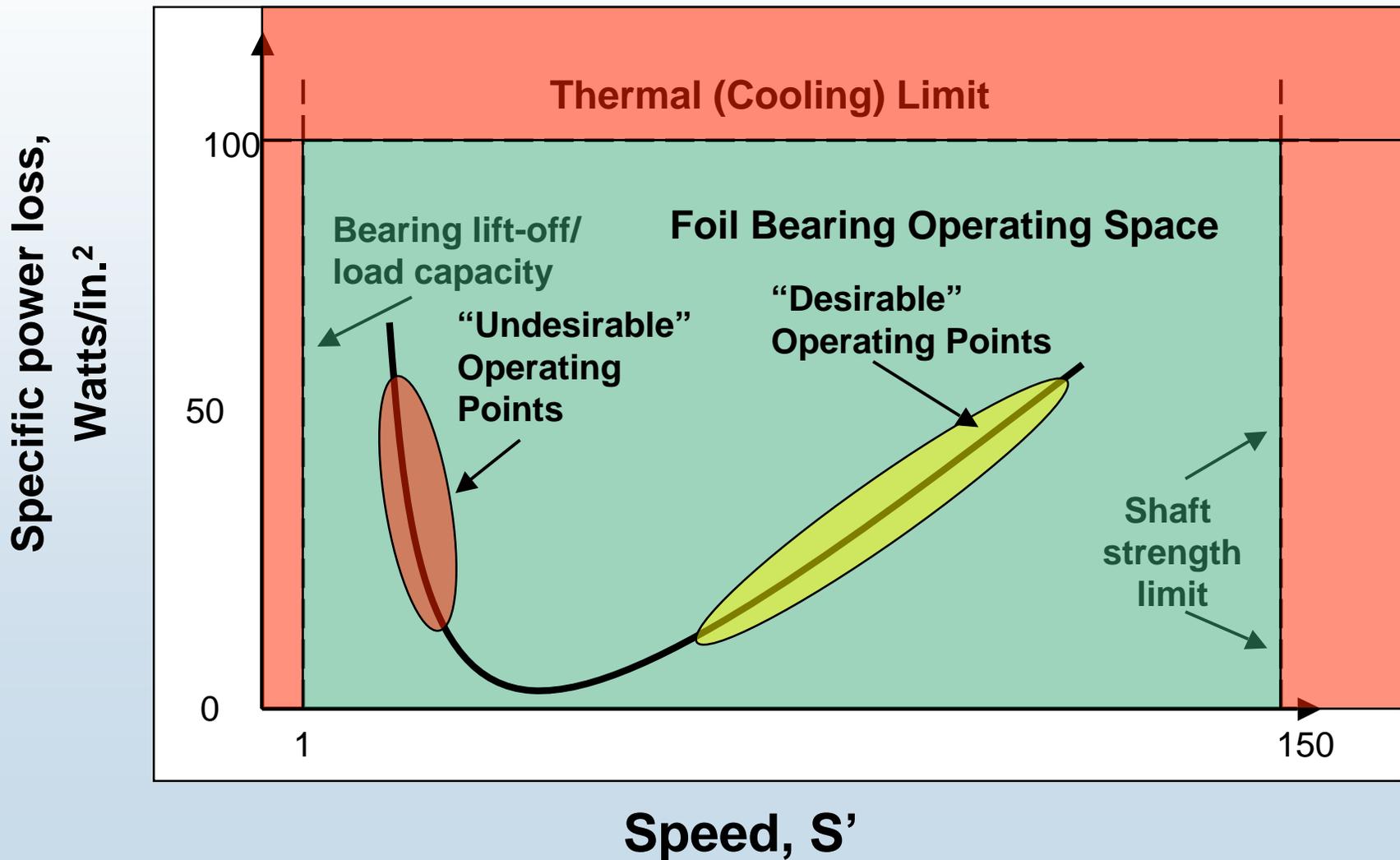
Foil Bearing Operating Map (Physical Limits to operating space)





Optimized Rotorcraft Propulsion System

Foil Bearing Operating Map (Physical Limits to operating space)





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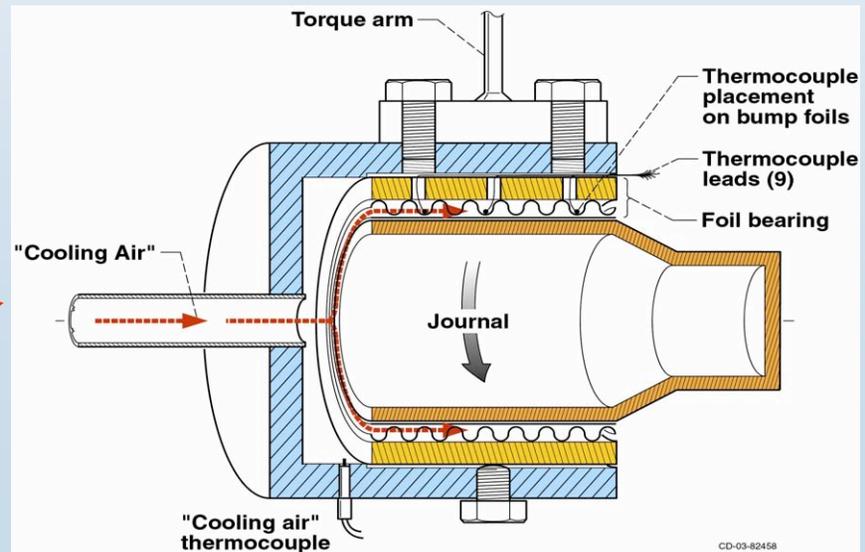
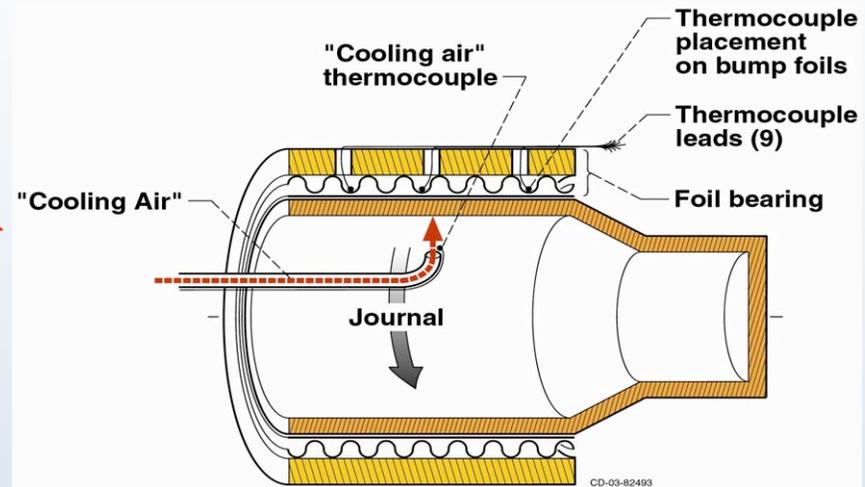
Thermal Management of Foil Air Bearings

Direct Cooling
of Journal



Cooling
Methods

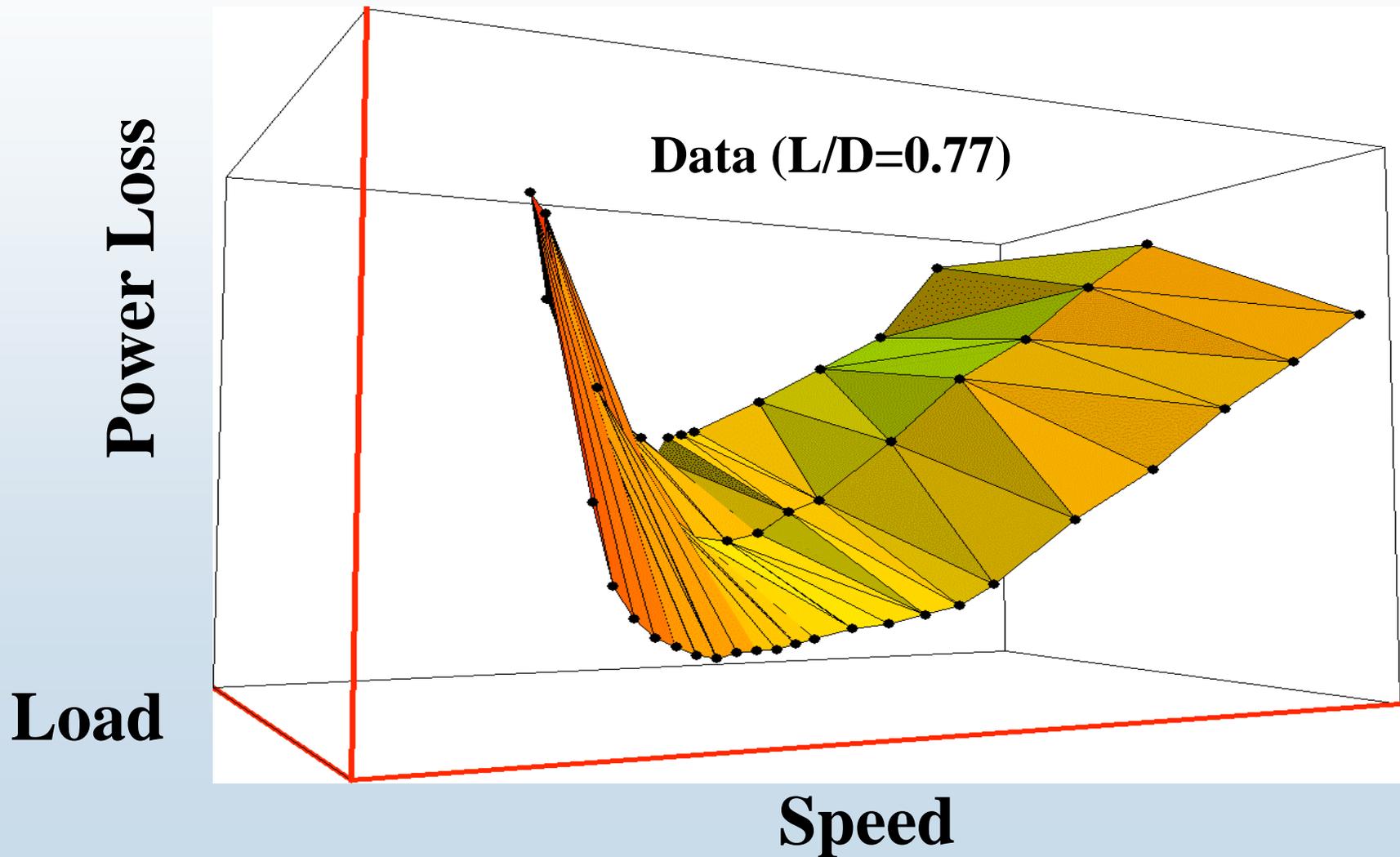
Direct
Cooling of
Bearing





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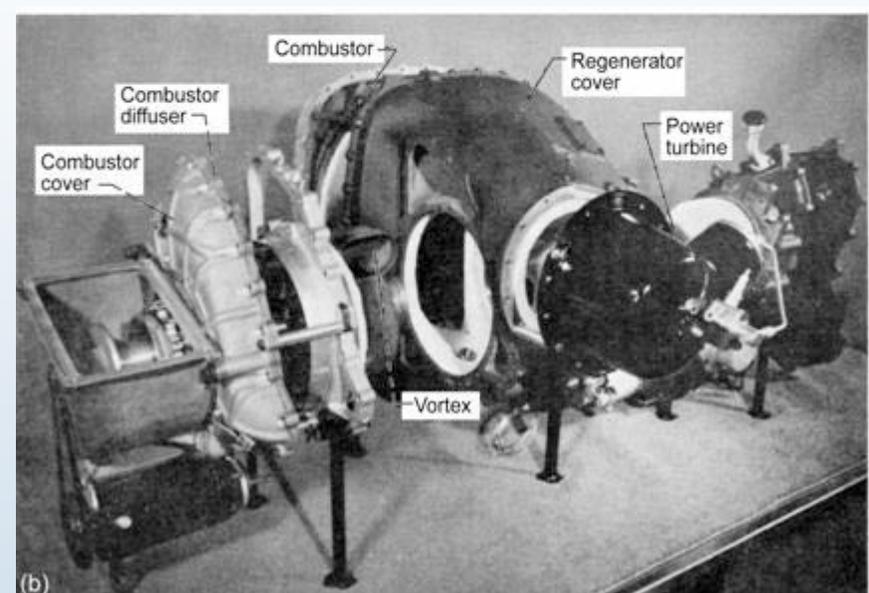
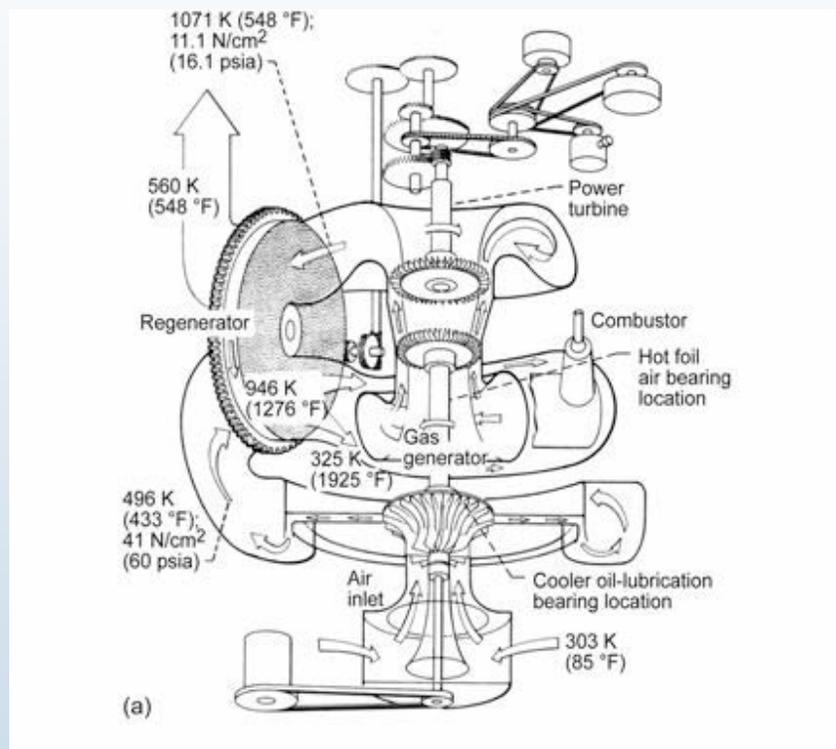
3-D Performance Map





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Optimized Rotorcraft Propulsion System



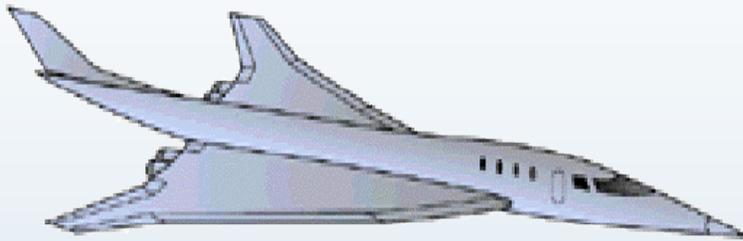
- The concept of thrust load sharing and coupling the power turbine to the transmission is not new.
- Successfully used in the DOE automotive gas turbine program.



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Oil-Free Propulsion System Study

RJ(7000 hp LPT) and SBJ (28000 hp LPT), T700 (2000 hp LPT)



- Assumptions
 - Oil-Free bearings will be interchangeable with rolling element bearings at some time in the future.
 - The effects of oil-free technology on thermodynamic parameter were estimated to be less significant than the effects on the flowpath layout and engine weight. Therefore, the engine cycles were left unchanged.
 - Higher rotational speeds may enable the design of lighter weight turbomachinery on the 50 passenger regional jet engine. Therefore, two benefit levels were analyzed.



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Oil-Free Propulsion System Study

<u>Feature</u>	<u>Cycle Change</u>	<u>Effect</u>
Eliminate oil / sump routing through flowpath	Reduce frame / IGV pressure drop	+
Provide excess air through the bearing for thermal stabilization	Increase bleed and secondary air flows	-
Increase bearing / bearing cavity temperature	Retain / add heat to engine cycle	+
<u>Feature</u>	<u>Flowpath/Weight Change</u>	<u>Effect</u>
Eliminate oil system	Reduce engine weight	+ (Calculated)
Eliminate tower shaft and accessory gearbox	Reduce engine weight	+ (Calculated)
Include Integral Starter / Generator and fuel pump motor	Add to engine weight	- (Calculated)
Eliminate oil / sump routing through the flowpath	Simplify and reduce weight of engine frames	+(Calculated)
Utilize bearings as secondary flowpath seals	Simplify and reduce weight of engine frames	+
Operate turbomachinery at higher shaft speed	Redesign turbomachinery to reduce weight (if DN limited)	+ (Calculated, one case only)
<u>Feature</u>	<u>Economic Change</u>	<u>Effect</u>
Eliminate oil system	Reduce maintenance cost	+
Reduce engine weight	Reduce acquisition cost	+
Reduce thrust requirement through sizing effects	Reduce acquisition and maintenance cost	+
Reduce turbomachinery parts count through high DN redesign	Reduce acquisition and maintenance cost	+
Immature ISG technology in difficult maintenance location	Increase cost	-



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Oil-Free Propulsion System Study

	50 PAX base	50 PAX base -11% remove oil	% improvement	50 PAX base -26% remove oil	% improvement	50 PAX MaxCase2	50 PAX MaxCase2 -11% remove oil	% improvement
Engine cycle								
Engine Weight Reduction								
Mission Mods								
TOGW	46870	46128	1.58%	45274	3.41%	44223	43665	1.26%
Block Fuel	5209	5138	1.36%	5059	2.88%	4043	4004	0.96%
Mission NOx	46	45	2.17%	44	4.35%	25	25	0.00%
LTO-NOx	13.9	13.8	0.72%	13.6	2.16%	2.8	2.8	0.00%

	SBJ base	SBJ base -9% remove oil	% improvement			SBJ MaxCase3	SBJ MaxCase3 -9% remove oil	% improvement
Engine cycle								
Engine Weight Reduction								
Mission Mods								
TOGW	111732	108666	2.74%			93063	91295	1.90%
Block Fuel	44626	43693	2.09%			37224	36767	1.23%
Mission NOx	1177	1157	1.70%			784	778	0.77%
LTO-NOx	30.2	29.4	2.65%			11.8	11.6	1.69%

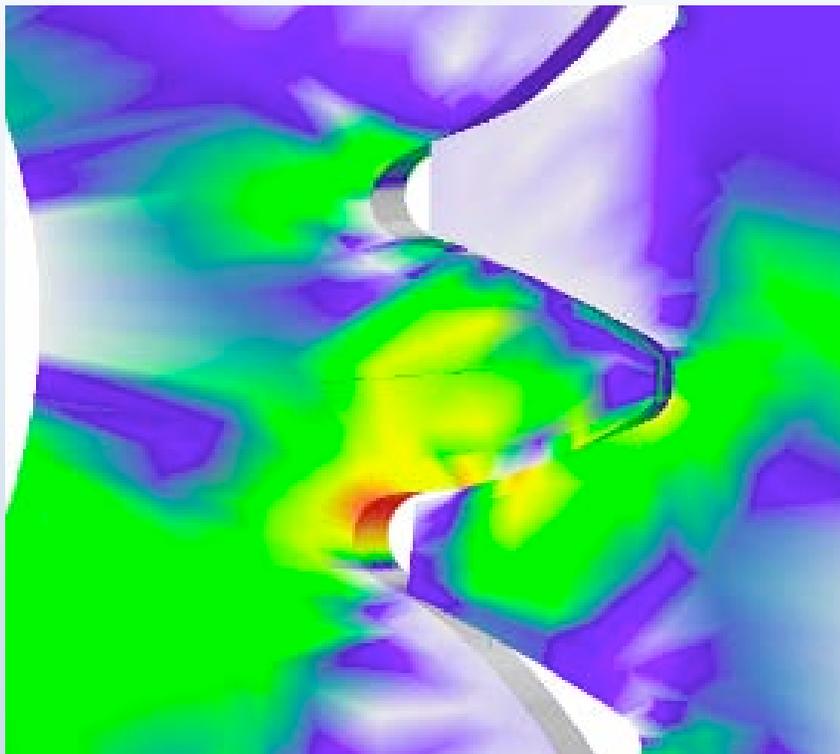
Engine weight reductions of 9-11% are achievable via bearing replacement and lube system removal

Engine weight reductions of 26% are achievable with higher speed turbomachinery designs



Optimized Rotorcraft Propulsion System

Transmission Advantages



- Research has shown that increasing oil viscosity by 30% can double gear fatigue life and by simultaneously improving additives tailored toward gears, fatigue life can be increase by over **8 times**.
- The logistical burden of a second lubricant can be mitigated by removing oil from the turboshaft engine.
- More work is needed in highly loaded gearboxes, an estimate of 2x improvement in power density is assumed.



Optimized Rotorcraft Propulsion System

Technical Challenges

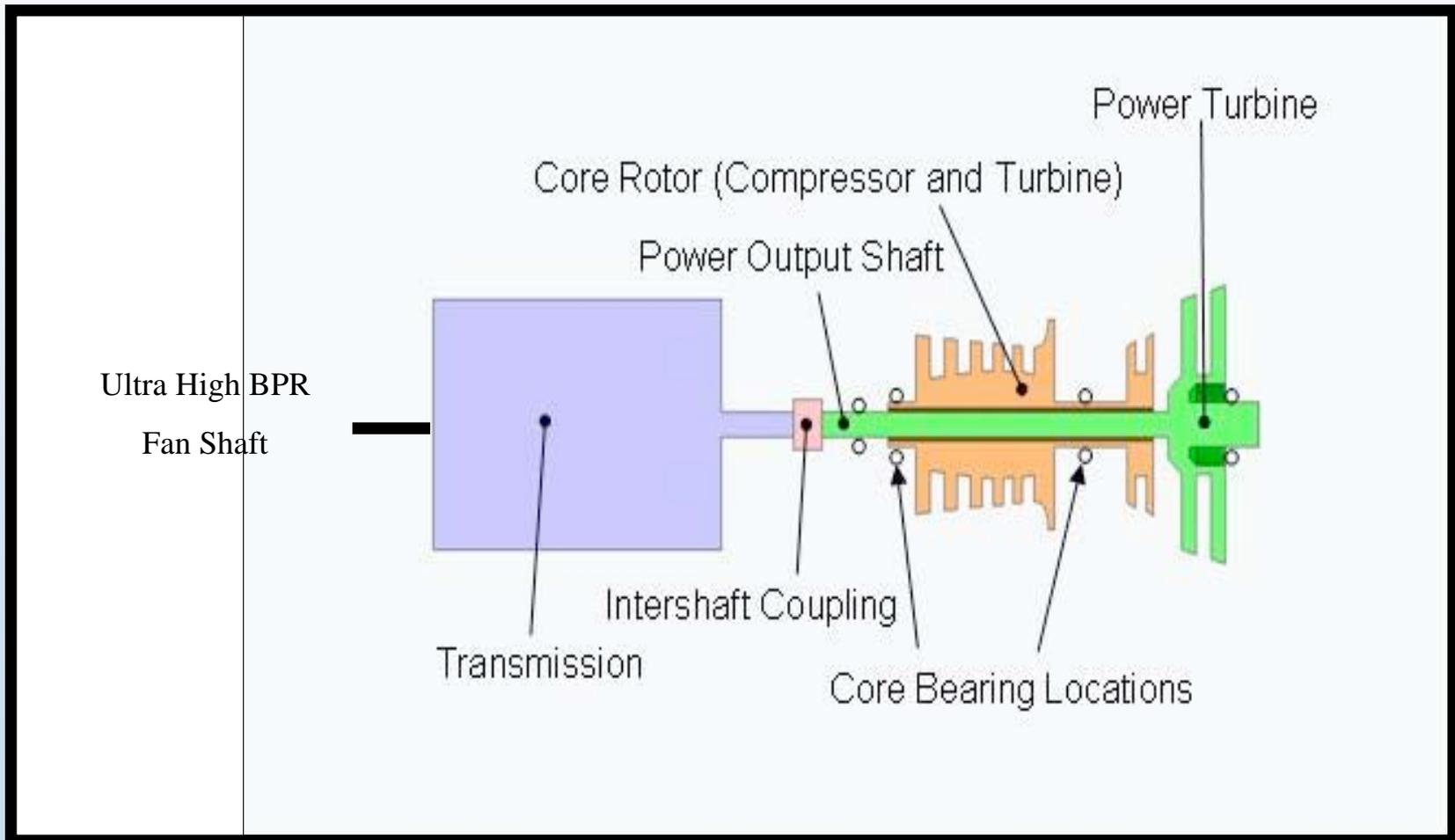
- New gas generator / turboshaft engine development program to fully capitalize on the advantages of oil-free turbomachinery.
- Axial alignment and thrust load management (minimization) is critical to oil-free turbomachinery.
- Oil free accessories such as integral starter generators will need to be developed and certified.
- Health monitoring instruments and field experience is necessary.
- Highly loaded, optimized gearboxes require ongoing research and development.



Optimized Rotorcraft Propulsion System

Cross-Cutting Applications

Optimized Turbofan Propulsion System?





Optimized Rotorcraft Propulsion System

Summary

- The optimized rotorcraft propulsion system which couples an oil-free turboshaft engine to a highly loaded gearbox that provides axial load support for the power turbine can be designed with current laboratory proven technology. Such a system can provide up to 60% weight reduction of the propulsion system of rotorcraft vehicles. Several technical challenges are apparent at the conceptual design level and should be addressed with current research. Axial alignment and thrust load management (minimization) is critical to oil-free turbomachinery.



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www.grc.nasa.gov/WWW/Oilfree